

Distributed Heterogeneous Simulation of a Hybrid-Electric Vehicle

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Hybrid-electric military vehicles provide many advantages over conventional military vehicles powered solely by diesel or turbine engines. These advantages include improved acceleration and fuel economy, stealth capability for silent mobility and silent watch, and ability to carry future energy weapons and advanced armor protection. The U.S. Army Research, Development and Engineering Command (RDECOM) and Tank Automotive Research, Development and Engineering Center (TARDEC) have sponsored the modeling and distributed simulation of a hybrid-electric vehicle as a design and validation tool for the development of future military vehicles. This paper describes the structure of the electrical/propulsion system of the vehicle, and the modeling of the components within this system. In particular, modeling of the prime mover (a diesel engine), the generator/motor, the vehicle control system, and other major components are discussed. Distributed simulation was accomplished using the Distributed Heterogeneous Simulation (DHS) tool. Specifically, the model of the system was divided into multiple subsystems, whereupon DHS was used to connect the subsystem models to form a synchronized simulation, which can be executed on one computer or multiple networked computers. In addition to increasing simulation speed, DHS also allows the interconnection between component models developed in different simulation languages, without requiring them to be translated into a common language. This advantage is particularly important if component models developed in other languages, likely from component manufacturers, are to be added to the vehicle model in the future. The performance of the vehicle system was evaluated under various operating conditions, and simulation results demonstrating the behavior of the system are presented.

I. Introduction

Hybrid-electric military vehicles provide many advantages over conventional military vehicles powered solely by diesel or turbine engines. These advantages include improved acceleration and fuel economy, stealth capability for silent mobility and silent watch, and ability to carry future energy weapons and advanced armor protection¹. The U.S. Army Research, Development and Engineering Command (RDECOM) and Tank Automotive Research,

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14. ABSTRACT Hybrid-electric military vehicles provide many advantages over conventional military vehicles powered solely by diesel or turbine engines. These advantages include improved acceleration and fuel economy, stealth capability for silent mobility and silent watch, and ability to carry future energy weapons and advanced armor protection. The U.S. Army Research, Development and Engineering Command (RDECOM) and Tank Automotive Research, Development and Engineering Center (T ARDEC) have sponsored the modeling and distributed simulation of a hybrid-electric vehicle as a design and validation tool for the development of future military vehicles. This paper describes the structure of the electrical propulsion system of the vehicle, and the modeling of the components within this system. In particular, modeling of the prime mover (a diesel engine), the generator/motor the vehicle control system, and other major components are discussed. Distributed simulation was accomplished using the Distributed Heterogeneous Simulation (DHS) tool. Specifically, the model of the system was divided into multiple subsystems, whereupon DHS was used to connect the subsystem models to form a synchronized simulation, which can be executed on one computer or multiple networked computers. In addition to increasing simulation speed, DHS also allows the interconnection between component models developed in different simulation languages, without requiring them to be translated into a common language. This advantage is particularly important if component models developed in other languages, likely from component manufacturers, are to be added to the vehicle model in the future. The performance of the vehicle system was evaluated under various operating conditions, and simulation results demonstrating the behavior of the system are presented.		

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Development and Engineering Center (TARDEC) have sponsored the modeling and distributed simulation of a hybrid-electric vehicle as a design and validation tool for the development of future military vehicles. This paper describes the structure of the electrical/propulsion system of the vehicle, and the modeling of the components within this system. Distributed simulation of the vehicle was accomplished by using Distributed Heterogeneous Simulation (DHS) tool. Example studies that were performed on this system are also presented.

II. System Structure

For the purpose of the study reported in this paper, a non-line-of-sight cannon (NLOS-C) demonstrator² vehicle is chosen, the information related to which vehicle was obtained from public domain sources. In particular, the electrical/propulsion system of the vehicle is shown in Fig. 1. As shown, a diesel engine and a generator/motor (G/M) that are connected to the transmission via torque couplers, form a parallel hybrid-electric drive system³. Depending on the commands, the torque couplers can individually engage and disengage. As a result, the vehicle can operate in three distinct modes, namely, the hybrid, the engine-only, and the motor-only (stealth) modes. In the hybrid and motor-only mode, the G/M can be commanded to operate as a motor to generate mechanical power to propel the vehicle; alternatively, it can be commanded to operate as a generator to convert mechanical energy from the diesel engine or from regenerative braking to electrical energy. A vehicle control module controls the operation of the engine and the G/M based on the user input and operating condition of the vehicle.

The G/M is connected to the high-voltage dc bus via a fully controlled three-phase bridge converter. Also connected to the bus are the Lithium-ion battery bank, the ultra-capacitor, and various electrical loads.

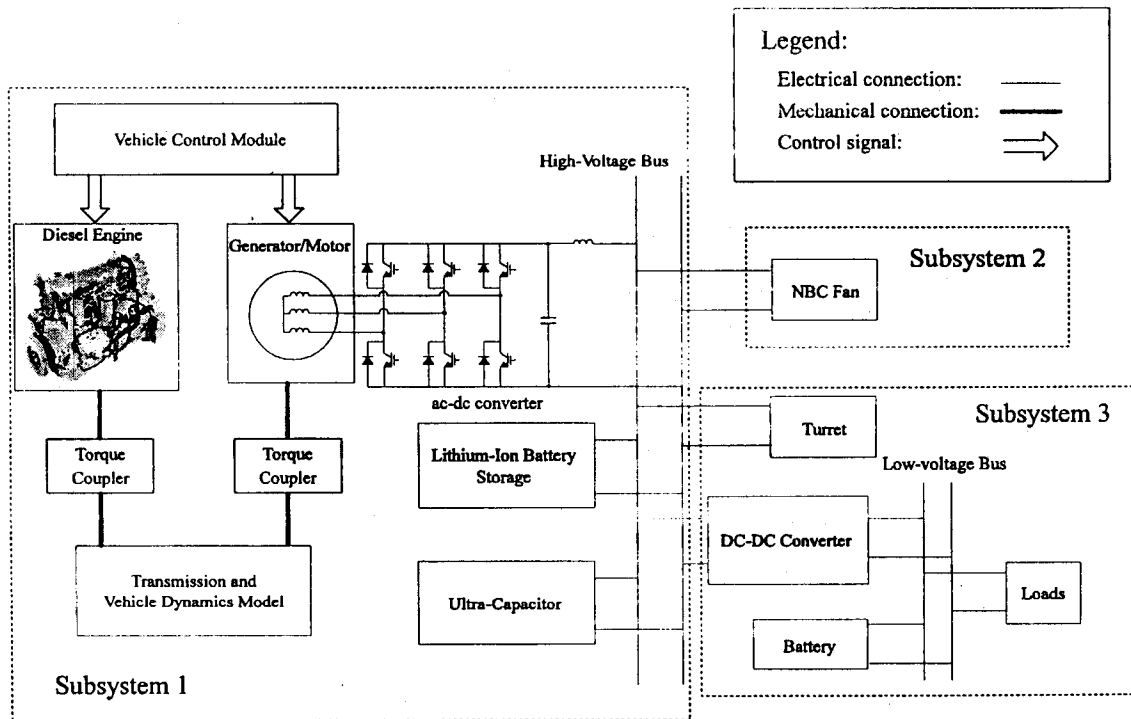


Figure 1. Structure of the electrical/propulsion system.

III. Component Models and GUI

The diesel engine power is modeled based on the following formula

$$P(\omega, C_h) = C_h(p_1\omega + p_2\omega^2 - p_3\omega^3) \quad (1)$$

where ω is the engine speed, and C_h is the throttle command ranging from 0 to 1. The coefficients p_1 , p_2 , and p_3 are determined based on the maximum engine power, the engine speed at maximum power, and the maximum engine speed⁴. The rate of fuel consumption at a certain throttle command and engine speed is calculated based on the fuel consumption map documented in Ref. 5.

The G/M is modeled as a permanent magnet synchronous machine⁶. The switching of the three-phase converter is controlled by a delta modulator⁶. The current command supplied to this modulator is synthesized based on the dc bus voltage, the motor speed, and the torque command to the motor. When the speed is low and the voltage is high, the synthesized current command ensures that the torque command to the motor is achieved while the current amplitude is minimized. Therefore, the motor is operating in the maximum-torque-per-ampere (MTPA) region⁶. As the motor speed increases and/or the dc voltage drops, the dc voltage can no longer support the current command within the MTPA region, and the field-weakening region is used. In this region, the commanded torque can still be achieved, albeit at the price of higher current amplitude. If the motor speeds up and/or the dc voltage drops even more, the commanded torque cannot be achieved without violating the voltage or current constraints. In this case, the current command is selected as the value that can generate the maximum torque without exceeding the voltage and current limits. The advantage of such current command synthesis strategy is that current tracking is always maintained. As a result, the low-frequency acoustic vibration generated by the motor drive subsystem is minimized.

The vehicle control module utilizes an algorithm similar to the one described in Ref. 8. Based on the throttle and brake pedal positions, vehicle mode of operation, and battery state of charge (SOC), this algorithm generates the throttle and torque commands to the engine and G/M, respectively.

The single-degree-of-freedom vehicle model takes into account the various forces on the vehicle, including rolling resistance and aerodynamic drag, gravity (on slopes), inertial forces (accelerating and decelerating), thrust forces from the engine and generator/motor, and braking forces from the mechanical brake and the generator/motor. A simple six-speed transmission is also included that up- and down-shifts at a series of predetermined speeds.

The energy storage devices in the propulsion system include the lithium-ion battery bank and the ultra-capacitor. Based on the range of the vehicle in the stealth model, the capacity of the battery bank can be estimated. In particular, 10 Saft VL modules are connected in series to form a battery pack. In turn, the battery bank is composed of 8 such battery packs connected in parallel for a total nominal capacity of 672 A-hrs at 216 V. The battery bank model is based on the equivalent circuit in Ref. 9, whereas the parameters are calculated based on the data sheet from the battery manufacturer. The ultra-capacitor is modeled as a simple capacitor without parasitic parameters.

Various electrical loads in the system, including a nuclear-biological-chemical weapon (NBC) protection fan, a turret, and a low-voltage (14 V) electrical system, are implemented to represent the typical loads present in a military vehicle¹⁰.

A convenient graphical user interface (GUI) is implemented in Matlab, as shown in Fig. 2. In this GUI, the vehicle speed (in mph), engine and G/M speed (in rpm), and gear selection are prominently displayed in a dashboard-like setting in the upper-right quadrant. Other performance data, including the instantaneous and average fuel economy, powers and torques of the engine and G/M, elevation, distance, battery SOC, total fuel consumption, and mission time are displayed in the lower-left quadrant. An energy monitor similar to those that can be found in consumer hybrid vehicles is placed in the lower-right quadrant, in which the appropriately highlighted arrows graphically indicate the power flow between the components in the vehicle. Within this GUI, the user can also conveniently select the operating model of the vehicle, give throttle and brake commands, and control the progress of the simulation.

IV. Distributed Simulation

To facilitate distributed simulation, the system is partitioned into three subsystems, as labeled in Fig. 1. The three subsystem models are connected using the Distributed Heterogeneous Simulation (DHS) tool¹¹. A 22-second example study was conducted, in which the vehicle accelerates from stop to about 26 mph before it brakes and comes to a stop again. The speed vs. time plot is shown in Fig. 3. As shown, the results from single model simulation and DHS are visually indistinguishable from each other. The simulation run times are listed in Table 1. By distributing the simulation onto 3 identical computers (Pentium 4, 3-GHz desktops), the simulation speed was increased by almost 5 fold. When all three DHS models are executed on the same computer, the simulation speed was more than twice the speed of a single model.

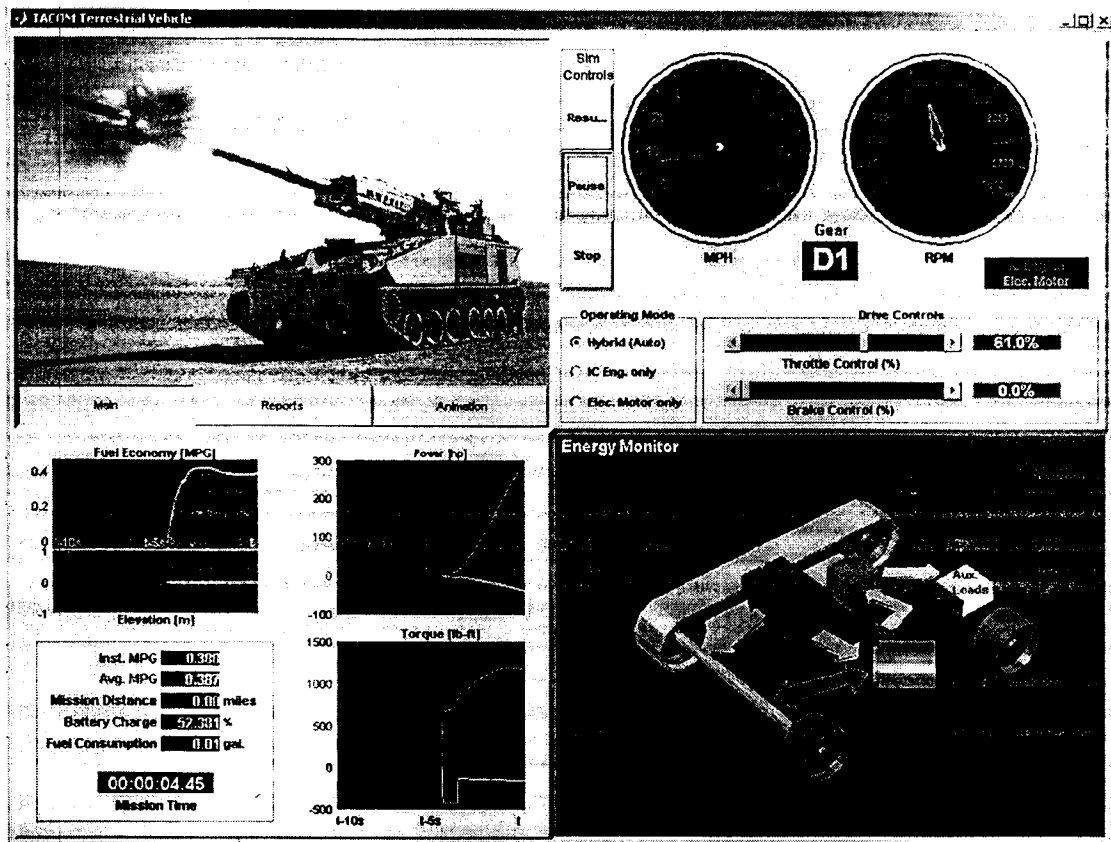


Figure 2. Graphical user interface.

Table 1. Simulation time comparison (22s study).

Simulation Type	Run Time	Relative Speed
Single model	3014s	100%
DHS on 3 computers	612s	493%
DHS on 1 computer	1268s	238%

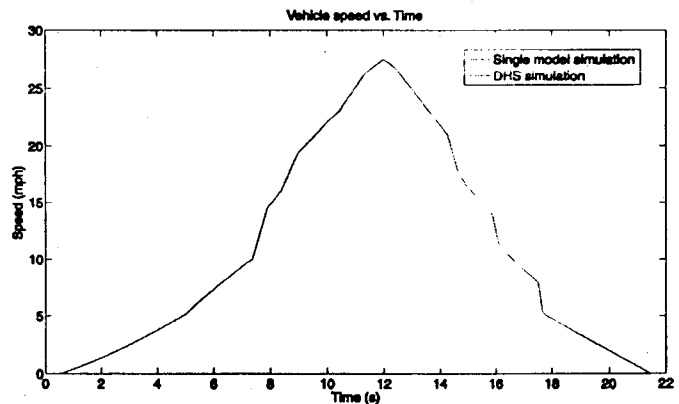


Figure 3. Single model and DHS simulation results.

A second example study was conducted to compare the performance of the vehicle in hybrid and engine-only modes. In this study, the vehicle travels through a test course with a profile shown in Fig. 4, which is similar to the grade test section of the US Army Aberdeen Test Center Monson course⁵. A speed regulator was used to enable the vehicle to achieve and maintain a preset reference speed. As shown in Fig. 4, at the start of the course, the vehicle is commanded to accelerate to 15mph. When the vehicle reaches the 36% incline, the speed command is reduced to 5mph, which is maintained through the 20% decline and the flat portion after the hill. At 180m, the vehicle is commanded to stop. The vehicle was simulated in both hybrid mode and engine-only mode. The speed response, fuel consumption, and battery charge under the two modes are compared in Fig. 5 - 7. As shown in Fig. 5, the vehicle accelerates faster in hybrid mode because of the assist from the electric motor. Because of the fast response

of the motor, the vehicle also maintains a more steady speed on the slopes. As shown in Fig. 6, the vehicle draws more electrical power from the battery during acceleration and hill climb in the hybrid mode. However, most of the energy is recovered through regenerative braking at the decline and final braking. Over the test course, the battery SOC decreases by the same amount in the hybrid mode and engine-only mode. However, as shown in Fig. 7, the vehicle operating in the hybrid mode consumes 28% less fuel than the engine-only mode during this test course.

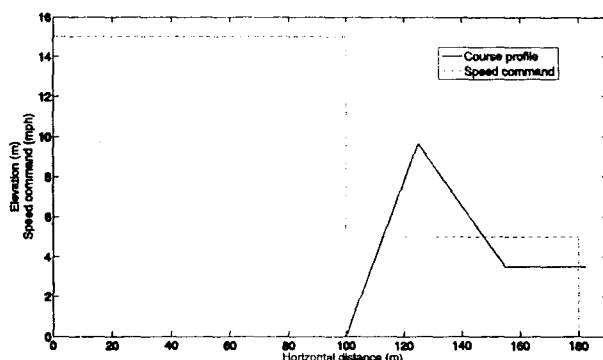


Figure 4. Test course profile and speed command.

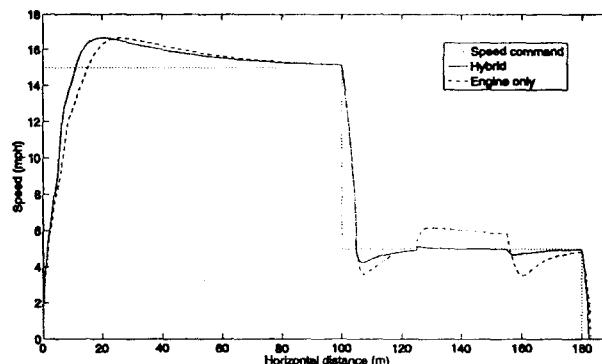


Figure 5. Vehicle speed.

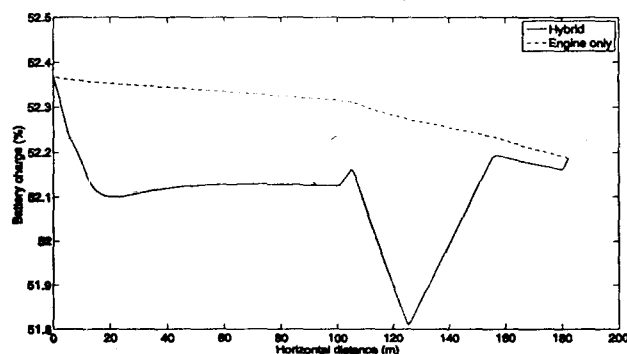


Figure 6. Battery SOC.

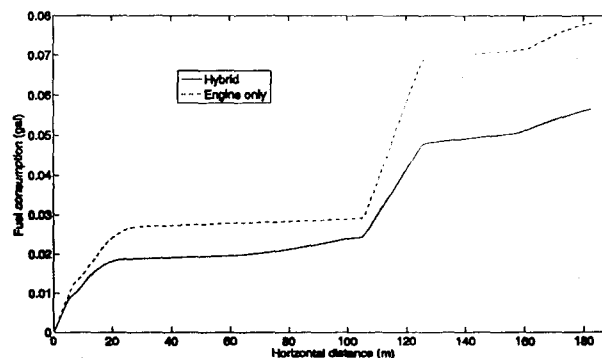


Figure 7. Fuel consumption.

V. Conclusions

The modeling and distributed simulation of a military hybrid-electric vehicle as a design and validation tool is presented in this paper. The structure of the electrical/propulsion system and the modeling of its component are discussed. It is shown through an example study that by partitioning the system and distributing the simulation, the simulation speed can be increased up to five times. A second example has demonstrated that the vehicle mode can be used to study the behavior and performance under different operating conditions.

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